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Modulating prefrontal control in humans reveals distinct pathways to competitive success and collective waste

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Abstract

Competitive decision making may require controlling and calculative mind-sets. We examined this possibility in repeated predator–prey contests by up- or down-regulating the individual's right inferior frontal gyrus (rIFG), a brain region involved in impulse inhibition and mentalizing. Following brain stimulation, subjects invested as predator or prey against a non-treated antagonist. Relative to sham-treatment (i) prey-defense was relatively frequent, strong and unaffected by stimulation, (ii) down-regulating predator rIFG produced a high-firing strategy—predators earned more because they attacked more frequently, while (iii) up-regulating predator rIFG produced a track-and-attack strategy—predators earned more because they attacked especially when their (non-stimulated) antagonist lowered its prey-defense. Results suggest that calculative mindsets are not needed to compete effectively, especially not when the goal is to survive. Enhanced prefrontal control enables individuals to appear less aggressive without sacrificing competitive effectiveness—it provides human predators with an iron fist in a velvet glove.

Key words: cooperation; aggression; defense; inferior frontal gyrus; theta burst stimulation

Introduction

Humans have strong capacity for large-scale cooperation with genetically unrelated others and unfamiliar strangers, allowing them to live in cohesive groups, to form complex social networks, and to establish well-functioning societies (Ostrom, 1998; Henrich *et al.*, 2001; Balliet and Van Lange, 2013). All too often, however, humans also create costly conflict over turf and territory, power and privileges, or ideas and ideologies (Rapoport, 1960; De Dreu, 2010). In fact, as observed by political economist John Stuart Mill (1859): 'a great proportion of all efforts in the world are…spent by mankind in injuring one another, or in protecting against injury', and such competitive tendencies may wreck families and neighborhoods, undermine work team effectiveness and decision quality, and hurt individual creativity and innovation (De Dreu, 2010). Yet, while these economic contests and social conflicts can be physically risky, emotionally depleting and collectively wasteful (Jervis, 1976; Abbink, 2012; Simunovic *et al.*, 2013), those individuals who win and prevent defeat increase their relative wealth and survival probability. Humans may thus be prepared not only for empathy and cooperation but also for competition (Dawkins and Krebs, 1979; De Dreu *et al.*, 2010; Rilling and Sanfey, 2011).

Competitive strategies and success has been associated with more calculative mindsets and controlled, deliberative decision making (Sanfey *et al.*, 2003; Knoch *et al.*, 2006; Bhatt *et al.*, 2010; Rand *et al.*, 2012; Halali *et al.*, 2013; De Dreu *et al.*, 2015a,b). If true, competitive decision making, and its effectiveness, may be associated with neural activation in the phylogenetically recent prefrontal cortex involved in executive control, decision planning and the inhibition of pre-potent responding (Rilling

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and Sanfey, 2011; Crone and Dahl, 2012). Here we pursued this possibility by experimentally manipulating the functionality of the prefrontal cortex while individuals made investment decisions in a competitive predator–prey contest (PPC) (Carter and Anderton, 2001; Abbink, 2012; De Dreu *et al*., 2015b). In this contest, two individuals (a 'predator' and a 'prey') simultaneously decide how much to invest out of a given endowment. Investments are wasted, but when predators invest more than their prey, they acquire the remainder of their prey's endowment, who is left with nothing; otherwise, predator and prey keep what is left of their endowments. Thus, while it is collectively wasteful to invest anything, predators may decide to invest to accumulate (relative) wealth, whereas prey may decide to invest to prevent loss and subordination (Abbink, 2012; De Dreu *et al*., 2015b; Carter and Anderton, 2001). Within such contests, predators and prey compete successfully when investments defeat their prey, and prevent defeat, respectively. These contests thus model key aspects of competition and conflicts between, for example, burglars and home owners, prosecutors and defense lawyers, terrorists and intelligence officers or industrial leaders preparing for *vs* protecting against hostile takeover.

The prefrontal cortex encompasses a variety of brain regions, each with distinct functionalities (Aron et al., 2003; Rilling and Sanfey, 2011; Crone and Dahl, 2012). Of pivotal importance to predator–prey competitions may be the right inferior frontal gyrus (rIFG), a prefrontal structure that comes to full maturation in late adolescence only (Shaw *et al*., 2008; Crone and Dahl, 2012). Of the range of socio-cognitive processes that are associated with the inferior frontal gyrus (for reviews see, e.g. Aron et al., 2003), established functionalities of the right hemispheric IFG include the regulation of self-control and impulse-inhibition (Aron *et al*. 2003; Chambers *et al*., 2007; Christopoulos *et al*., 2009; Casey *et al*., 2011; Jacobson *et al*., 2011). In addition, the rIFG has been implicated in mentalizing—the ability to take another's perspective and to predict another's behavioral intentions and choices (De Lange *et al*. 2008; Halko *et al*., 2009; Kuo *et al*., 2009). Both self-control and mentalizing are core processes in social interaction in general, and in competitive contests specifically (e.g. Decety et al., 2004; Edmonds *et al*., 2012; Molenberghs *et al*., 2015).

In both human and non-human animals, defensive aggression recruits sub-cortical circuitries involved in intuitive responding, whereas aggression geared at subordinating others and appropriating their resources is typically more controlled and calculated (De Dreu *et al*., 2015b; Nelson and Trainor, 2007). In predator–prey competitions, the rIFG may thus be more important for predation than for prey-defense. Specifically, in predators, the rIFG may enable two distinct processes relevant to competitive decision making. First, because down-regulated rIFG associates with reduced self-control and impulse-inhibition, down-regulated rIFG may enable heuristic rather than pre-meditated competition that manifests itself in a 'high-firing' strategy—relatively frequent attacks unconditioned by the history of competitions and the antagonist's (defensive) behavior. Second, because up-regulated rIFG associates with enhanced impulse-control and mentalizing, up-regulated rIFG may enable close monitoring of one's prey to predict when prey-defenses will be low and predator attack to be successful and beneficial. Up-regulated rIFG would thus manifest in a 'track-and-attack' strategy—relatively in-frequent attacks that are conditional upon the history of competitions and the antagonist's (defensive) behavior.

Methods and materials

Overview

Our study involved a double-blind sham-controlled cross-over experiment with 18 healthy males who participated in three sessions (Figure 1A). One to three months prior to the experiment, participants underwent neuro-imaging to localize the rIFG (Figure 1B), and at the beginning of a session, they received neuro-navigated theta-burst stimulation (TBS) to temporarily down-regulate (cTBS), up-regulate (iTBS) or leave unaffected (imTBS) their rIFG (order was randomized across sessions and participants). TBS is a form of transcranial magnetic stimulation that manipulates a brain region for 2 min only, with effects lasting up to 40 min (Huang *et al*., 2005; also see Hamada *et al*., 2012). In each session, participants played a 40-trial incentivized PPC twice, once as predator and once as prey (each 40-trial block paired to a new antagonist who was naïve to the treatment applied to the participant). On each PPC-trial, one individual (henceforth predator) decides how much to invest in predation (X) out of a €10 endowment (with $0 \leq X \leq €10$), while the other individual (henceforth prey) simultaneously decides how much to invest in defense (Y) (with $0 \leq Y \leq €10$). Accordingly, we observed 18 participants $\times$ 3 (sessions) $\times$ 2 (blocks) $\times$ 40 (trials) $=$ 4320 investment decisions by participants, and another 4320 investment decisions by their non-treated antagonists.

Participants and ethics

A total of 36 healthy male individuals participated in three sessions, with 7–10 days in between sessions. Eighteen underwent TBS-treatment (henceforth 'participants') and another 18 did not receive any treatment (henceforth 'antagonists'). Non-treated antagonists were matched to participants in terms of sex and age (range 20–28, $M = 25.16 \pm 2$). Participants underwent medical screening to minimize possible adverse effects of neuroimaging and TBS-treatment. We screened participants on history of seizures, neurological diseases and other factors that may pose a risk for the application of TMS (Rossi *et al*. 2009). In addition, and to ensure they were able to provide full informed consent, eligible participants were invited for a pre-treatment experience. In total, 20 people participated in this pre-treatment session, in which they were shown the machineries and allowed to experience the TBS-treatment (4 s of stimulation). Two individuals withdrew from participation and 18 continued.

The experimental procedures, materials and treatments received ethics approval from the Psychology Institute Ethics Review Board of the University of Amsterdam (file AO-2501). Prior to each session, participants and non-treated antagonists received an information package about the study, detailing the specific procedures and possible adverse effects. Upon reading these, participants and antagonists provided written informed consent. During sessions, at least one experimenter present had a first aid certificate and medical assistance was available on call. Neither experimenters nor participants reported any undesirable or worrying effects of TBS-treatment. This was confirmed when participants were contacted by phone 12–24 h following participation. The TBS-treatment appeared well-supported without adverse effects.

Experimental procedures and timelines

Participants and non-treated antagonists all participated in three sessions, in which they played one block of 40-trials as predator and one block of 40 trials as prey (order

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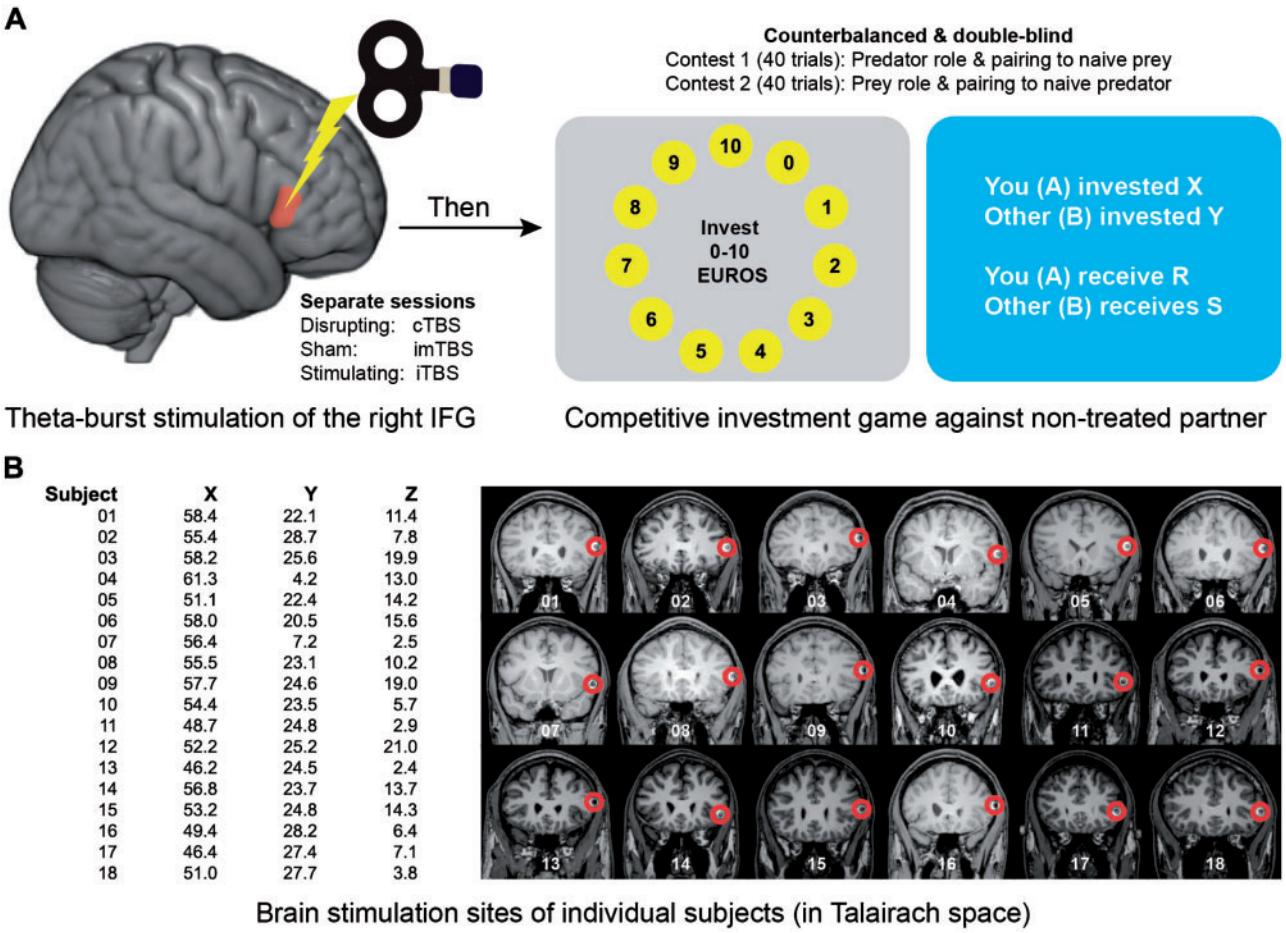

Subject	X	Y	Z
01	58.4	22.1	11.4
02	55.4	28.7	7.8
03	58.2	25.6	19.9
04	61.3	4.2	13.0
05	51.1	22.4	14.2
06	58.0	20.5	15.6
07	56.4	7.2	2.5
08	55.5	23.1	10.2
09	57.7	24.6	19.0
10	54.4	23.5	5.7
11	48.7	24.8	2.9
12	52.2	25.2	21.0
13	46.2	24.5	2.4
14	56.8	23.7	13.7
15	53.2	24.8	14.3
16	49.4	28.2	6.4
17	46.4	27.4	7.1
18	51.0	27.7	3.8

Fig. 1. Experimental methods and procedures. (A) Timeline of one (of three) experimental session. (B) Individual brain stimulation sites from anatomical MRI scans and the concomitant right inferior frontal gyrus coordinates in Talairach space that served as inputs for neuro-navigated TBS.

counterbalanced between participants and across sessions). Participants and antagonists were scheduled so that for each block the participant was matched to a new antagonist that had the same level of experience with the game (e.g. when a participant in session 2 started his third block, and thus had experience with two contest blocks, he was paired to a new antagonist that also had played two blocks of trials in a previous session but with different participants).

For participants each session lasted approximately 2.5 h for which they received a standard show-up fee of €30. Antagonists received a standard show-up fee of €7 for each 45-min session in which they participated. Both participants and antagonists could also earn up to €45 based on their decisions (across all three sessions additional pay could range between €0 and 135). As announced prior to each session, additional pay was based on a random draw of three trials for each block played and resulted in mean additional earnings over the three sessions of €66.33 ± 26.45 per person. Earnings were added to the show-up fees and transferred to the individual's bank account.

Experimental procedures during a session differed between participants and antagonists. The participants were scheduled to arrive 45 h before the other participants would arrive. Upon arrival, participants received all information including consent forms and instructions for the PPC game. Then they underwent one of three types of TBS-treatment (see TBS-specification and Localization of the rIFG below). Thereafter, participants were escorted to another laboratory, where their (non-treated) antagonist was already present and prepared for the PPC. Antagonists were in individual cubicles, and participants were assigned a different individual cubicle. Each cubicle was equipped with a personal computer that was linked across cubicles; participants and antagonists could not see or hear each other.

Antagonists were scheduled to arrive at the laboratory 15 min before the participant would enter, in order to receive game instructions and fill in the consent form. To avoid losing sessions because of unforeseen circumstances with TBS treatment, we always scheduled and prepared more than one antagonist. Excess antagonists were paid their show-up fee and dismissed without participating.

Once the participants were seated in the Behavioral Lab the PPC was started (see Predator–Prey Contest below). Upon completion of the session, antagonists received a debriefing and left, while the participants were escorted back to the TBS-laboratory for 45 min of resting time. This ensured that the effect of the TBS-treatment wore off completely before participants left the laboratory. Within 24 h following treatment, participants were contacted by phone to identify potential issues, and nothing was revealed.

The experiment was carried out double-blind. The TBS procedure and the behavioral experiment were supervised by two different groups of experimenters. The experimenters for the behavioral experiment were unaware of what TBS-treatment a particular participant received, and those in the TBS-laboratory

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were absent during the PPCs and unaware of the starting roles participants would be assigned to.

TBS specifications and localization of the rIFG

TBS was delivered with the use of a 3.5 T MagStim Rapid^2 Stimulator (Magstim Co., UK) and a figure-of-eight shaped coil (70-mm outer diameter). Before the experiment commenced, we determined the active motor threshold of each individual. We followed the guidelines of the International Federation of Clinical Neurophysiology (Rossini *et al.*, 1994; also see Hinder *et al.*, 2014) to determine the minimum intensity that induced a visible movement to the contralateral first interosseus dorsalis muscle. Subsequently, we aimed the TMS coil at the right IFG. The location of this area was determined, for each subject, with the use of an anatomical MRI (per Figure 1A and B). We aimed the Transcranial Magnetic Stimulation (TMS) coil at the posterior and ventral part of the inferior frontal gyrus *pars triangularis* with the use of the Visor system and dedicated ANT software (ANT—Visor system; ant-neuro.com). Specifically, 1–3 months prior to the first experimental session, TBS-parties were brain-scanned to localize their rIFG. Three-dimension TFE T1 weighted images were acquired using a 3T Achieva TX scanner (Philips, The Netherlands) (time to echo (TE) 3.8 ms; repetition time (TR) 8.2 ms; flip angle (FA) 8°; 160 sagittal slices of 1 mm; field of view (FOV), 2562 mm; reconstruction matrix, 2562 mm, 358 s). These images were used together with the Visor neuro-navigation system to locate the rIFG pars triangularis for each participant.

The TBS was applied using a Magstim Rapid^2 stimulator. A figure-8-coil was used, set at 80% of the active motor threshold. Three types of stimulations were used, intermittent- (iTBS), intermediate- (imTBS) and continuous TBS (cTBS). As the name suggests, cTBS consists of a continuous stream of pulses which decreases the excitability of the cortex, therefore decreasing IFG activity. During iTBS 2 s of pulses are followed by 8 s of rest. This stimulation sequence increases cortex excitability and will boost IFG activity. Finally, during iTBS 5 s of pulses are followed by 10 s of rest. In this stimulation sequence facilitating and inhibitory effects cancel each other out, maintaining the subject's baseline IFG excitability, also referred to as sham stimulation. For all of the TBS treatments the total amount of received pulses added up to 600 (Huang *et al.*, 2005).

Predator–prey contest

The PPC Game (PPCG; De Dreu *et al.*, 2015b) involves two players, each with an endowment E. One individual (henceforth predator) decides how much to invest in predation (X) out of his or her endowment *E* (with $0 \leq X \leq E$, with E = €10), while the other individual (henceforth prey) simultaneously decides how much to invest in defense (Y) out of an equal endowment *E* (with $0 \leq Y \leq E$, with *E* = €10). If $X > Y$ then the predator obtains all of *E*–*Y*; added to the remaining endowment *E*–*X*, this leads to a total predator payoff of: $2E - X - Y$, while prey is left with 0. If $X \leq Y$ then predator appropriates nothing, leading to a payoff of *E*–*X* for the predator and *E*–*Y* for the prey.

The PPCG is formally equivalent to a contest with a contest success function $f = X^m/(X^m + Y^m)$, where *f* is the probability that the predator wins, $m \to \infty$ for $X \neq Y$, and $f = 0$ if $Y = X$ (Tullock, 1980; De Dreu *et al.*, 2015b). Assuming rational selfish behavior, with *E* = €10, the following mixed strategies for predator (with probability of investing *X* denoted by *p*(X)) and prey (with probability of investing Y denoted by *p*(Y)) define a unique Nash equilibrium for PPCG: Predator: $p(X = 1) = 2/45$, $p(X) = p(X - 1)[(12 - X)/(10 - X)]$ for $2 \leq X \leq 6$, $p(X = 0) = 1 - [p(X = 1) + \ldots + p(X = 6)] = 0.4$, and $p(X) = 0$ for $X \geq 7$; Prey: $p(Y) = 1/(10 - Y)$ for $0 \leq Y \leq 5$, $p(Y = 6) = 1 - [p(Y = 0) + \ldots + p(Y = 5)] = 0.15$, and $p(Y) = 0$ for $Y \geq 7$. Accordingly, in the PPCG it is collectively irrational and wasteful to invest in either predation or defense, because the money invested is lost for both predator and prey. Nevertheless, it is individually rational to invest, as indicated by the Nash equilibrium. On average, prey is expected to invest $Y = 3.38$ per trial and predator $X = 2.62$, and the frequency of attack (expected number of trials in which an investment is made; range 0–40) equals 24 for predator and 36 for prey (De Dreu *et al.*, 2015b). Given the same logic, predators are expected to earn an average of 10, whereas preys are expected to earn an average of 4.

The PPCG was programmed in Presentation (Neurobehavioral Systems) and was self-paced. Participants and antagonists were explained the rules of the game prior to the first trial of each of two 40-trial blocks. It thus was explained that investments were always lost, that when the predator (labeled Role A) invested more than the prey (labeled Role B) the predator received what was left of his own endowment in addition to the remainder of his prey's endowment, and that if prey invested equal or more than the predator both players would keep what remained of their own endowment after the investment round.

At the beginning of each trial, both predator and prey received an endowment of €10 and were prompted to make an investment between 0 and 10. After each investment decision, players received feedback (i.e. they saw each other's investment decision along with the payout to themselves and to their other player) (see also Figure 1A). Upon finishing a 40-trial block, there was a short break and roles and partners switched and players played a second block of 40 trials. TBS-treated players' starting role was varied between subjects and across sessions following a counterbalanced (Latin Square) predetermined schedule.

Measures and data analytic approach

Data analyses were restricted to participant decisions and outcomes. We computed the following indices. Overall investment was defined as the investment choice per trial, ranging between 0 and 10 (per Figure 1A). To examine the emergence of a high-firing strategy *vs* track-and-attack strategy, we computed frequency as whether, on a particular trial, an investment was made or not (coded as 1 = yes, 0 = no); reported is the proportion of investment decisions across 40 trials (range 0–40, linearly corresponding to 0.0–1.0). The high-firing strategy implies higher attack frequency that is not conditioned by the history of play, whereas the track-and-attack strategy implies a lower attack frequency that is conditional upon the antagonist's behavior on previous rounds of the PPCG.

The PPCG allows the computation of several performance indicators. We focused on two indicators of performance—competitive success, and personal earnings. Competitive success was defined as investments decisions being made ($X,Y > 0$) resulting in victory to predators (i.e. non-treated prey's earning = 0 on that trial) or prey survival (i.e. prey earning > 0). Personal earnings were operationalized as the amount of money earned on a particular trial (range €0–€19 for predators, and €0–€10 for prey). We note that competitive success and personal earnings are qualitatively different aspects of performance, and both indices need not be correlated. For example, a predator who invests 1 out of 10 has a low probability of

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competitive success, yet secures an earning of either (9; when $Y > 0$) or 19 (when $Y = 0$); a predator who invest 9 has a high probability of defeating its prey, yet earns either 0 (when $Y \geq 9$) or between 1 and 11 (when $Y < 9$).

Data were analyzed using generalized linear multilevel models (GLMM), which allowed us to include all sampled datapoints in the analysis without the necessity to average over trials, time points or decision makers within a dyad (Aarts *et al.*, 2014; Kret *et al.*, 2015). Accordingly, dependency in the data is accounted for, all variance in the data is maintained and with the possibility to include fixed and random factors, the statistical model can be set up in such a way that it most optimally explains this variance. Statistical models for overall investment, frequency, competitive success and personal earnings held a four-level structure, i.e. trial (level 1), nested in Role (level 2), nested in Treatment (level 3), nested in participants (level 4). First-order autoregressive (AR1) covariance structures were added to control for auto-correlation, and random effects were included to control for individuals, session order and block.

We expected no effects for treatment in prey, and specific effects for treatment in predators. Accordingly, and to limit the number of tests, only when we observed a significant treatment × role interaction we proceeded by (i) examining a treatment effect within each role and then (ii) within predators further decomposing the contrast between sham-treatment and (up or down) TBS for predators (but not for prey). These decompositions are listed in the Results section; Fixed-effects for the overall models are summarized in Table 1.

Results

Investment decisions

In 90% of all 4320 paired decisions, at least one dyad member invested in predation or prey-defense ($X,Y > 0$). Inspection of the frequency distributions of investment choices (Figure 2A and B) shows that participants do invest, that investments are spread, and that prey invest more than predators. Deviating from what standard rational economic theory would predict (*7,13,34*), however, participants also over-invest ($X,Y \geq 7$), which theoretically should not happen. Furthermore, whereas the distribution of investment choices for prey is similar across TBS treatment (Figure 2A), predator investment does differ, especially in the frequency of 'no-attack' decisions ($X = 0$) (Figure 2B).

Table 1. Test-statistics for GLMM-analyses of participant's behavioral strategies and outcomes as a function of (interactions among) treatment, role and trial

	Investment	Frequency	Success	Earnings
Corrected model[a]	31.353***	86.318***	142.946***	217.263***
Treatment	0.038	0.127	2.972§	0.534
Trial	7.698**	4.524*	1.448	1.493
Role	48.025***	148.010***	395.959***	540.221***
Treatment × trial	0.134	0.003	2.143	1.464
Treatment × role	3.629¶	4.417*	3.753*	5.136**
Trial × role	0.037	0.020	0.283	0.528
Treatment × trial × role	0.205	0.012	2.074	2.607

Note.
[a]Entries are F-values for fixed effects, with $3.081 < Df2 < 4.312$.
¶$P = 0.056$.
*$P < 0.025$.
**$P < 0.005$.
***$P < 0.001$; Models included random effects for participant, and participant × session number and first-order autoregressive covariance estimates for participant × session number × block.

The patterns seen in Figure 2A and B were confirmed in GLMM-analyses of overall investments, and investment frequency. Prey invested more than predators ($F = 48.025$, $P = 0.001$), and this difference was somewhat but not significantly increased when the rIFG was up- rather than down-regulated (Figure 2C; Role × Treatment, $F = 3.629$, $P = 0.057$). More robust effects emerged for attack frequency (Figure 2D). For frequency, the role × treatment interaction was significant ($F = 4.417$, $P = 0.036$). As predicted, prey were not influenced by treatment ($F = 1.0922$, ns). However, predators invested more often when their rIFG was down-regulated relative to sham-treatment ($F = 4.490$, $P = 0.034$), and rIFG up-regulation ($F = 5.341$, $P = 0.025$).

Competitive strategies: high-firing vs track-and-attack

In subsequent analyses we examined whether and how treatment modulated performance, operationalized as competitive success and personal earnings. Competitive successes were influenced by treatment ($F = 2.972$, $P = 0.051$) and treatment × role ($F = 3.753$, $P = 0.024$). Prey survived most of their predator attacks, independent of treatment ($M_{down} = 76.4\%$ *vs* $M_{sham} = 80.1\%$ *vs* $M_{up} = 75.0\%$; $Fs < 1.88$, $ps > 0.15$). Among predators, both competitive success and personal earnings were conditioned by treatment, albeit in rather different ways depending on whether the rIFG was down- or up-regulated.

We considered first predators with down-regulated (*vs* sham-treated) rIFG and found evidence for a 'high-firing' strategy. Relative to sham-treatment, down-regulated rIFG produced more attacks (per Figure 2D), more competitive successes (Figure 3A; $F = 5.451$, $P = 0.020$), and higher personal earnings (Figure 3B; $F = 11.189$, $P = 0.001$). Indeed, attacks predicted personal gain when rIFG was down-regulated rather than sham-treated (Figure 3C; $\beta = 1.460$, $t = 3.750$, $P = 0.001$; attack × treatment, $F = 14.059$, $P = 0.001$). This reveals that with reduced prefrontal control, predators adopt a rather aggressive high-firing strategy that in dynamic competitions is relatively effective.

Next we considered predators with up-regulated (*vs* sham-treated) rIFG and found little evidence for this 'high-firing strategy.' Up-regulated rIFG did not lead to more attacks (per Figure 2D) or to greater competitive success (Figure 3A; $F = 1.976$, $P = 0.160$). Although up-regulating rIFG (*vs* sham-treatment) did lead to higher personal earnings (Figure 3B, $F = 9.992$, $P = 0.002$), earnings were not predicted by attack frequency (Figure 3C; $\beta = 0.445$, $t = 1.274$, $P = 0.213$; attack × treatment, $F = 2.100$, $P = 0.148$). Instead, we found that predators with up-regulated rIFG engaged in, and benefitted from, a 'track-and-attack' strategy. We computed an index for change in the non-treated antagonist's prey-defense in the two rounds previous to the (TBS-treated) predator investment decision (subtracting prey-investment on trial-1 from trial-2; theoretical range $\Delta\text{-Prey} = -10$ to $+10$). This Δ-Prey was not influenced by predator's rIFG-treatment (all $F \leq 0.198$, $P \geq 0.657$), and predator attacks lowered Δ-Prey ($\beta = -0.264$, $t = -2.121$, $P = 0.034$).

Analyses focusing on predator investments showed that relative to sham-treatment, up-regulated rIFG caused predators to attack more when Δ-Prey was negative rather than positive (Figure 4A; Treatment × Δ-Prey, $F = 6.188$, $P = 0.010$). Put otherwise, when prey lowered their defenses, predators with up-regulated rIFG (relative to sham) were more likely to invest. Importantly, this differential tracking of Δ-Prey also explained higher earnings when predator rIFG was up-regulated (Figure

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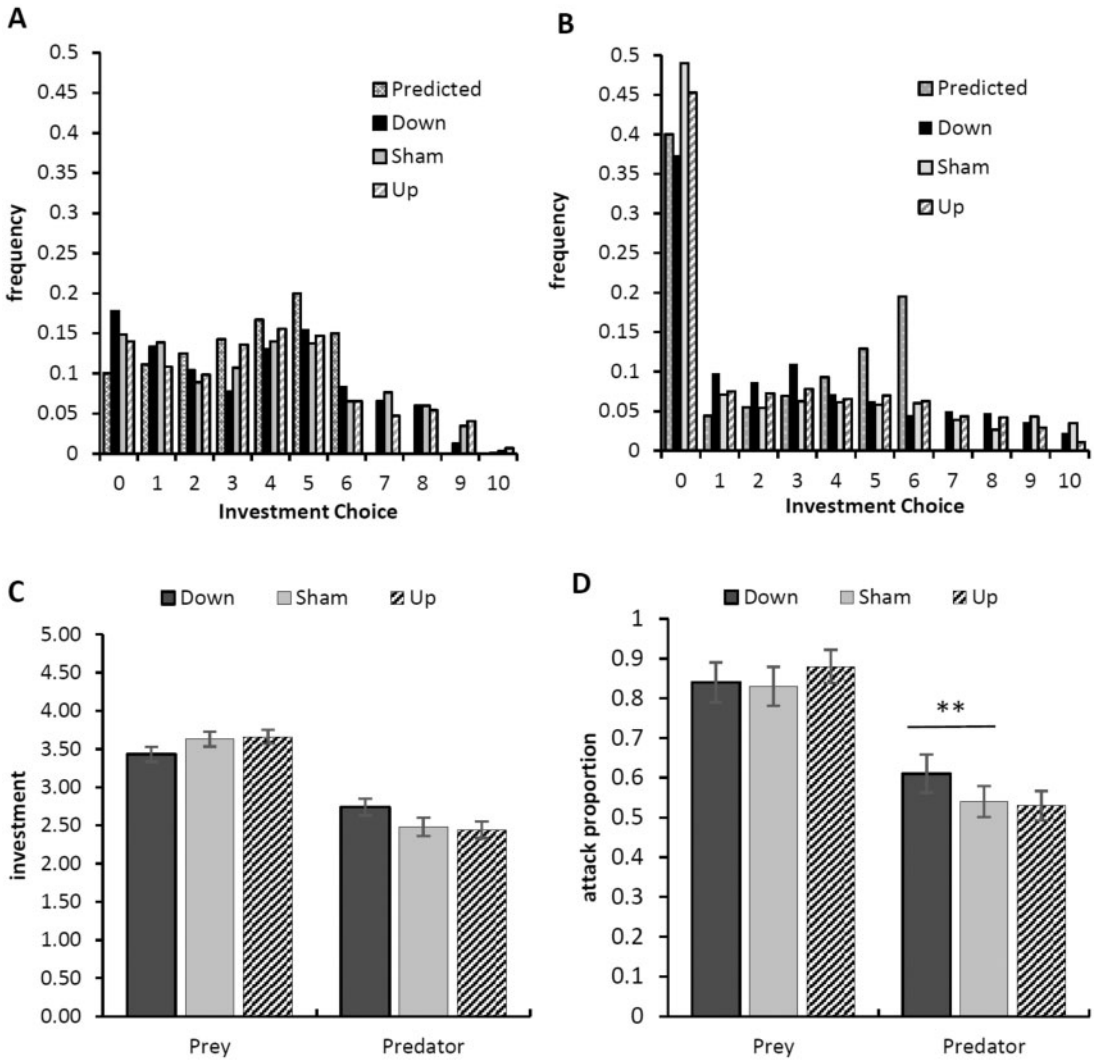

Fig. 2. Participants' investment decisions in their role as predator and prey. (A) Distribution of investment decisions by prey, broken down by treatment and compared with predicted values based on standard rational choice theory (game theory expects no prey investments ≥7). (B) Distribution of investment decisions made by predators, broken down by treatment and compared with predicted values based on standard rational choice theory (game-theory expects no investments ≥7). (C) Investment as a function of treatment and role (displayed Mean ± SE). (D) Attack (X,Y > 0) as a function of treatment and role (range 0.0–1.0 corresponding to 0–40 attack decisions; displayed mean ± SE; * $P \leq 0.05$; ** $P \leq 0.005$).

4B, relative to sham-treatment: Treatment × Δ-Prey, $F = 4.081$, $P = 0.044$). (Sham-treated predators did not differ from predators with down-regulated rIFG [Treatment × Δ-Prey, $F = 0.849$, $P = 0.357$]). Thus, with up-regulated rIFG predators conditioned their attacks more on lowered prey-defense, and therefore earned more than when they had received sham-treatment.

Conclusions and discussion

In the dynamic predator–prey competitions studied here, individuals in the role of prey invested frequently in defense and their competitive strength was unaffected by experimental manipulation of their rIFG. Possibly, competitive behavior geared at protection and avoiding injury is relatively impulsive and may be modulated primarily by subcortical brain circuitries involved in threat-detection and emotion-based decision (LeDoux, 2000; Nelson and Trainor, 2007; Delgado *et al.*, 2008; De Dreu *et al.*, 2015b). Quite in contrast to this, we observed individuals in the role of predator to be influenced by experimental manipulation of their prefrontal functionalities, in terms of the competitive strategies they employed, their competitive successes, and their personal earnings. With relaxed prefrontal control, and concomitant higher risk tolerance and reduced impulse inhibition (Aron *et al.*, 2003; Chambers *et al.*, 2007; Casey *et al.*, 2011; Jacobson *et al.*, 2011), predators engaged in a 'high-firing' strategy that brought them competitive success and increased personal earnings. With enhanced prefrontal control, and concomitant increased impulse-control and ability to mentalize (De Lange *et al.*, 2008; Halko *et al.*, 2009; Kuo *et al.*, 2009), predators engaged in a 'track-and-attack' strategy that is less aggressive overall, but equally beneficial in terms of personal earnings.

The interpretation of our results hinges on the assumption that intermittent TBS (i-TBS) raised prefrontal excitability, while continuous TBS (c-TBS) lowered excitability. Strongest evidence for this assumption derives from meta-analyses revealing that when applied to the motor cortex c-TBS indeed reduces excitability, while i-TBS increases excitability (Wischnewski and

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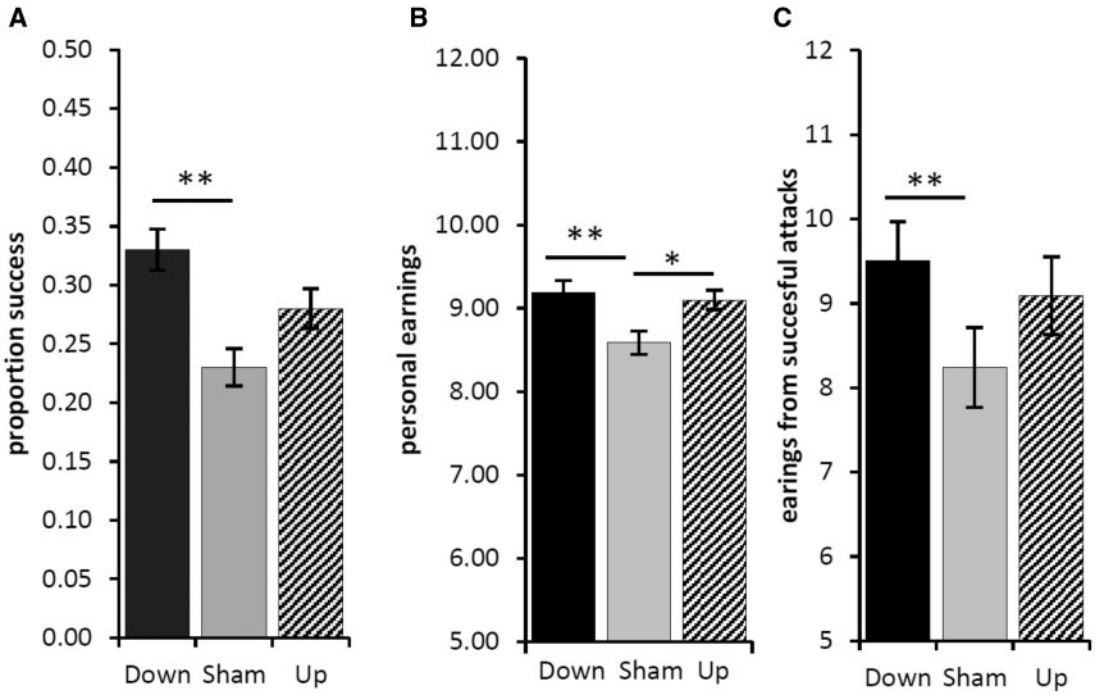

Fig. 3. Emergence and effectiveness of predator's high-firing strategy. (A) rIFG-treatment predicts predator's competitive success (range 0.0–1.0 proportionate to 40 possible victories; displayed mean ± SE; * $P \leq 0.05$; ** $P \leq 0.005$). (B) rIFG-treatment predicts predator earnings (range €0–€19; displayed mean ± 2SE; * $P \leq 0.05$; ** $P \leq 0.005$). (C) Predator earnings from attacks as a function of rIFG-treatment (range €0–€19; displayed mean ± 2SE; * $P \leq 0.05$; ** $P \leq 0.005$).

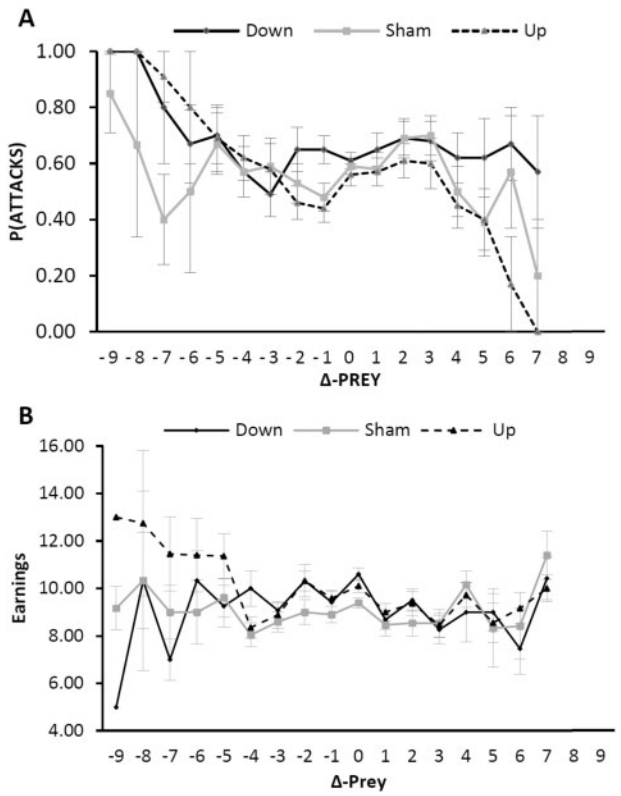

Fig. 4. Emergence and effectiveness of predator track-and-attack strategy. (A) rIFG-treatment and Δ-Prey predict predator attack (range 0.0–1.0 proportionate to 40 possible victories; Δ-Prey values for −10, −9, +10 are not displayed because of low (<2) observations; displayed mean ± SE). (B) rIFG-treatment and Δ-Prey predict predator earnings (range €0–€19; Δ-Prey values for −10, −9, +10 are not displayed because of low (<2) observations; displayed mean ± SE).

Schutter, 2015; Chung *et al.*, 2016). Our study is, however, one of the first that applied TBS to cognitive/non-motor regions in competitive contests, and it may be that the neural mechanisms producing the observed changes in behavior are due not only to changes in excitability in the right IFG, but caused also by changes in more distal cortical and/or subcortical brain regions. However, while TBS can produce temporary changes in deeper neural structures, or create network imbalances, the amount of TBS pulses given (600 pulses in all three TBS conditions), the location of stimulation (exactly the same location), and the intensity of stimulation was all tightly controlled across all different TBS conditions, and both i-TBS and c-TBS differed from sham-treatment as predicted. Future work in this area could merge TBS-treatment with neuro-imaging to verify that, indeed, our treatments selectively increased or decreased activity in the rIFG and explore which neural circuitries and networks are affected, and how.

Our results can be understood well in terms of risk-tolerance, inhibition of pre-potent responding, and mentalizing ability—functionalities typically associated with the rIFG. Nevertheless, two issues need to be addressed. First of all, there is some evidence that rIFG-associated capacity for mentalizing is involved in empathic responding (Shamay-Tsoory *et al.*, 2009). Empathic responding may be more prevalent among predators than among prey, who can afford empathic errors less than predators. Results fit the idea that up-regulated rIFG enhances mentalizing, but reveal also that in competition and conflict such mentalizing ability serves calculated attack rather than pro-social approach. Possibly, rIFG-associated capacity for mentalizing can be either 'cold' or 'hot,' depending on whether the context determines whether others are primarily seen as antagonistic competitors, or as allies and potentially deserving others with whom one wishes to cooperate (Decety and Cowell, 2014; Keysers and Gazzola, 2014).

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Second, at a conceptually broader level, it may be that down-regulating (up-regulating) the rIFG increased (reduced) relative left-hemispheric approach motivation and reduced (increased) right-hemispheric avoidance motivation (Harmon-Jones, 2003; Nash *et al*., 2010; Roskes *et al*., 2011; Brookshire and Casasanto, 2012). Possibly, such enhanced approach motivation accounts for the high-firing strategy we observed in predators with down-regulated rIFG, and increased avoidance motivation explains the track-and-attack strategy we observed in predators with up-regulated rIFG. However, whereas rIFG activity has been linked to biobehavioral approach/avoidance (e.g. Gable *et al*., 2015; but see Dambacher *et al*., 2015), we are unaware of established linkages between approach motivation and a preference for high-firing strategy, and avoidance motivation and a track-and-attack strategy. Thus, whether and how the rIFG—strategy linkage during competitive contests is mediated by biased biobehavioral approach/avoidance is a promising target for new research.

By experimentally manipulating the region within the human prefrontal cortex that regulates executive control and mentalizing, we uncovered a particularly pivotal role of prefrontal control in competitive interactions, and obtained strong evidence for the plasticity of the human brain—2 min of TBS shifted the brain from on-setting high-firing vs track-and-attack, and these effects lasted for at least 40 min of intense competition. This malleability occurred even within a particular experimental session, as participants switched from predator to prey roles and with that, up-or down-regulating the rIFG stopped or started to affect the type of competitive strategy employed. When self-defense is the key goal, prefrontal control and deliberative decision making appeared to be of little importance. However, when the individual aims at self-expansion and the accumulation of (relative) wealth, disrupted prefrontal control enables a high-firing strategy that is relatively aggressive and collectively wasteful. With enhanced prefrontal control, in contrast, individuals were able to suppress such aggressive impulses until their prey was likely to be most vulnerable. Enhancing the functionality of the right hemispheric inferior frontal gyrus provides human predators with an iron fist in a velvet glove.

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